# ON THE RESILIENCE OF INTERNET INFRASTRUCTURES IN PACIFIC NORTHWEST TO EARTHQUAKES

by

JUNO MAYER

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THESIS ABSTRACT

Juno Mayer

Bachelor of Science

Department of Computer and Information Sciences

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The U.S. Pacific Northwest (PNW) is one of the largest Internet infrastructure hubs for several cloud and content providers, research networks, colocation facilities, and submarine cable deployments. Yet, this region is within the Cascadia Subduction Zone and currently lacks a quantitative understanding of the resilience of the Internet infrastructure due to seismic forces. The main goal of this work is to assess the resilience of critical Internet infrastructure in the PNW to shaking from earthquakes. To this end, we have developed a framework called ShakeNet to understand the levels of risk that earthquake-induced shaking poses to wired and wireless infrastructures in the PNW. We take a probabilistic approach to categorize the infrastructures into risk groups based on historical and predictive peak ground acceleration (PGA) data and estimate the extent of shaking-induced damages to Internet infrastructures. Our assessments show the following in the next 50 years: $\sim$65% of the fiber links and cell towers are susceptible to a very strong to a violent earthquake; the infrastructures in Seattle-Tacoma-Bellevue and Portland-Vancouver-Hillsboro metropolitan areas have a 10% chance to incur a very strong to a severe earthquake. We also perform a case study of Integra's long haul links in the PNW and show that links between Portland and Seattle are at greatest risk of damage. To mitigate the damages, we have designed a route planner capability in ShakeNet. Using this capability, we show that a dramatic reduction of PGA is possible with a moderate increase in latencies via backup routes and new deployments that minimize cost and PGA. We also show that cell tower corridors can be reinforced to maintain wireless connectivity between metro areas in a disaster scenario.

CURRICULUM VITAE

NAME OF AUTHOR: Juno Mayer

UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene, OR, USA

DEGREE AWARDED:

Bachelor of Science, Computer and Information Sciences, 2021, University of Oregon
Secondary Academic Discipline, Audio Technology, 2021, University of Oregon
Secondary Academic Discipline, Mathematics, 2021, University of Oregon

AREAS OF SPECIAL INTEREST:

Software Engineering
Audio Technology
Network Measurements

PROFESSIONAL EXPERIENCE:

Researcher, Oregon Networking Research Group, Summer 2020 - Winter 2021
Research Assistant, School of Journalism and Communication, Fall 2019 - Winter 2021
Resident Assistant, University of Oregon Housing and Residence Life, Fall 2019 - Spring 2020
Research Assistant, University of Oregon Institute of Neuroscience, Fall 2018 - Summer 2019

GRANTS, AWARDS AND HONORS:

Outstanding Undergraduate Researcher Honorable Mention, Computing Research Association, 2020

PUBLICATIONS:

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TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

# CHAPTER I

# INTRODUCTION

Internet infrastructures—composed of nodes (e.g., data centers, colocation facilities, Internet eXchange Points or IXPs, submarine landing stations, cell towers, and points of presence or POPs) and links (e.g., short- and long-haul fiber-optic cables, and submarine cables)—play a crucial role in our day-to-day activities and public safety. For example, earthquake early warning systems such as ShakeAlert Given et al. (2018) rely on resilient Internet infrastructures to effectively detect, respond to, and recover from earthquakes. With 47% of trans-Pacific submarine cables in the west coast arriving onshore in Pacific Northwest (PNW)—37% in Oregon and 10% in Washington—a large presence of hyperscale cloud providers, and thousands of miles of metro- and long-haul fiber-optic cables Durairajan, Barford and Barford (2018); Durairajan, Barford, Sommers and Willinger (2015); Kumaran Mani, Hall, Durairajan and Barford (2020); Liu, Bischof, Madan, Chan and Bustamante (2020), the PNW is undoubtedly a regional locus of critical Internet infrastructure.

Geographically, the PNW is the site of the Cascadia Subduction Zone (CSZ) known to create large magnitude (**M**) 9 subduction (megathrust) earthquakes, as well as more frequent deep earthquakes occurring within the subducting oceanic crust ("inslab"), and shallower earthquakes in the continental crust. This tectonic setting poses a significant hazard to the region, capable of producing several meters of rapid ground deformation, as well as strong ground accelerations from shaking. Seismic hazard describes the expected frequency of shaking in a region and is a combination of the region's tectonic activity (i.e., areas with faults that release more energy from earthquakes contribute to greater seismic hazard), as well as factors that affect levels of shaking (e.g., amplification from shallow sediment). Typically shown as the probability of exceeding a particular level of shaking, seismic hazard represents a long-term average of the maximum shaking that may be felt due to many faults (seismic sources). Shaking can be represented by intensity measures such as peak ground acceleration or PGA (i.e., in fractions of $g$, 9.81m/s/s), or the qualitative Modified Mercalli Intensity (MMI) scale (e.g., severe, violent, etc.).

Recent global earthquakes have demonstrated that shaking and its associated hazards can have a large impact on telecommunications infrastructure and negatively affect post-disaster recovery. For example, the 2016 **M**7.8 Kaikōura crustal and megathrust earthquake caused significant damage to buried fiber-optic cables and microwave towers on New Zealand's South Island, leading to outages for up to five days Giovinazzi et al. (2017). The **M**9 2011 Tohoku-Oki subduction earthquake resulted in connectivity losses for 2 days Fukuda et al. (2011), and the **M**6.9 1995 Kobe crustal earthquake disconnected telecommunications infrastructure and isolated the cities of Kobe, Ashiya, and Nishinomiya *The Kobe Earthquake: Telecommunications Survives at Kobe University* (n.d.). In short, standard Internet infrastructures are not designed to be resilient to strong earthquake shaking.

To date, few studies Esposito et al. (2018); Fukuda et al. (2011); Leelardcharoen (2011) have considered how to assess and mitigate the effects of earthquake damage on Internet infrastructures, and none have investigated the potential impacts in the PNW. This is primarily due to two key issues. First is the paucity of high-quality Internet infrastructure maps that reveal dependencies between service providers and alerting systems, and the associated risks that are both intrinsic (e.g., infrastructure risks due to conduit sharing among providers Durairajan et al. (2015)) as well as extrinsic (e.g., infrastructure outages due to natural disasters Durairajan et al. (2018); Eriksson, Durairajan and Barford (2013a); Esposito et al. (2018); Leelardcharoen (2011); Padmanabhan, Schulman, Levin and Spring (2019); Schulman and Spring (2011)). Second is the inter-disciplinary nature of the problem: that is, it is not fully known what the impacts of shaking and seismic hazard are on Internet infrastructure, even from past earthquakes, due to the lack of collaborative efforts between network measurements and earth science communities.

To address these issues, we design *ShakeNet*: a framework to study the impacts of earthquake-induced shaking on the Internet infrastructure. At the core of ShakeNet is the probabilistic approach to (a) categorize Internet infrastructure of varying types into risk groups (e.g., data centers in *very strong* shaking areas vs. colocation facilities in regions that might experience *violent* shaking) and (b) estimate the extent of potential shaking-induced damages to Internet infrastructures. Our approach is built atop ArcGIS *ESRI ArcGIS.* (n.d.) and their application to the following datasets: (a) probabilistic seismic hazard analysis (PSHA) estimates of shaking in the CSZ, for the highest level of peak ground acceleration (PGA) that may occur within the next 50 years, and (b) Internet infrastructure datasets from diverse network measurement efforts Baker (2008); Durairajan et al. (2018, 2015); Kumaran Mani et al. (2020).

Using ShakeNet, we seek answers to the following research questions: (a) How much infrastructure—both nodes and links—is susceptible to earthquake shaking and shaking-induced damages in the PNW? (b) What are the impacts of shaking-induced outages on society? and (c) How can we minimize the impacts of earthquakes on Internet infrastructure deployments? To answer these questions, we examine >40,000 miles of fiber, 59 colocation facilities, 422 POPs, 4 IXPs, 31 data centers, and 213,554 cell towers in the PNW. We find that 71% of metro fiber have a 2% chance of experiencing 0.34g of PGA (severe shaking) in the next 50 years, and 27,781 miles (65%) have a 10% chance of experiencing 0.18g PGA or greater (very strong shaking). Of the nodes, 14% are in locations with a 2% chance of exceeding 0.34g PGA, and a 10% chance of exceeding 0.18g PGA within the next 50 years. Besides these nodes, 66.5% of towers have a 2% chance of experiencing 0.34g PGA or greater, and 67% have a 10% chance of feeling 0.18g PGA within the next 50 years. Overall, the areas with the highest level of potential impact are the Seattle-Tacoma-Bellevue metro in Washington and the Portland-Vancouver-Hillsboro metro in Oregon as they contain the highest concentration of wired and wireless infrastructure as well as a 10% chance to incur very strong (0.29 average) to severe (0.39 average) shaking within the next 50 years.

In addition to a cross-provider analysis of all PNW fiber, we perform a case study of Integra's fiber network to assess the risk of a given metropolitan area has of being disconnected. We find that the Seattle is at the greatest risk of being disconnected from Integra as it posesses only two long haul links leading to the area and the largest PGA values of any PNW metro area (10% chance of 0.29g and 2% of 0.40g)

Finally, we extend the ShakeNet framework with *route planner* capability to identify alternate fiber deployment routes that are geographically longer but are less susceptible to shaking vs. existing routes that are more prone to earthquake-induced shaking. While standard routing protocols employ backup paths to deal with connection interruptions e.g., due to outages, they are oblivious to this tradeoff space and are not robust to earthquakes and shaking risks. Identifying the alternative deployment locations by navigating this tradeoff space is the third contribution of this work. We show that route planner can be used to maximize the safety of infrastructure deployments and fiber networks. For example, data transfers between nodes in Seattle and Portland metros can be re-routed via the eastern PNW through Kennewick and Boise in the case that fiber running across the I-5 interstate is affected by damaging shaking. While this path is longer (i.e., $\sim$1200 miles), it has the benefit of being even further away from the CSZ and less adverse to risk (PGA reduction of 0.11 g for 2% probability of exceedance in the next 50 years).

We make further use of the *route planner* to perform a cost analysis of augmenting the PNW's fiber network with new links built along state roads that increase redundancy while minimizing length and the potential for shaking-induced damages. Assuming new fiber is deployed on existing state roads, we show that the most cost-effective deployments to increase redundancy are between Medford-Diamond Lake, Bend-Shedd, and between Portland and Seattle.

We also employ the *route planner* on the PNW's cell towers to establish the location of a cell tower backbone which, if reinforced, would provide connectivity between metro areas if they become disconnected from the wired fiber network. Using the route planner on cell towers involves building an ArcGIS *Network Dataset* from point data. To accomplish this, we create a custom ArcGIS toolbox to generate a line network of cell-tower connectivity based on an average 15 mile range. We show that the cell tower backbone which services all metros in the shortest path lies along the I-5 highway.

# CHAPTER II

# BACKGROUND AND MOTIVATION

**Seismic Hazard in the PNW.** Seismic hazard is defined as the expected frequency of *shaking*, not the frequency of earthquakes; the shaking is what causes damage to infrastructures (e.g., power lines, fiber cables, right of ways, etc.). For any given location, seismic hazard is the shaking expected over integration of all possible sources and shaking, a combination of two factors: (1) The nearby sources of seismic energy (e.g., faults) and how much energy they release over time; seismic sources are determined based on geologic and geophysical studies of a region and are controlled by the tectonic setting McGuire (1995); and (2) The shaking expected from all these surrounding seismic sources. Larger magnitude earthquakes, and closer earthquakes both cause stronger shaking.

Expected shaking is represented by intensity measures (IMs) and is estimated from empirical ground-motion models (GMMs) Joyner and Boore (1982). IMs vary and include: the peak value of ground motion recorded such as the peak ground acceleration (PGA) reached, the peak spectral acceleration (peak shaking convolved with a damped oscillator of the given period), or maybe described qualitatively, such as by Modified Mercalli Intensity (MMI) which categorizes ground-motion according to the perceived shaking experienced by an observer (shown in Table 1). In this study, we focus on PGA and MMI.

To represent the expected frequency of shaking, seismic hazard is typically reported for various "return periods" of interest, or for a probability of exceedance within a specified time interval. The specified time interval is chosen based on the application at hand—the typical life of a structure is considered to be ∼50

| PGA Value (g) | MMI Intensity | MMI-correlated Perceived Shaking |
|---|---|---|
| $<$ 0.0017 | I | Not Felt |
| 0.0017 - 0.014 | II - III | Weak |
| 0.14 - 0.039 | IV | Light |
| 0.039 - 0.092 | V | Moderate |
| 0.092 - 0.18* | VI* | Strong* |
| 0.18 - 0.34 | VII | Very Strong |
| 0.34 - 0.65 | VIII | Severe |
| 0.65 - 1.24 | IX | Violent |
| $>$ 1.24 | X | Extreme |

Table 1. PGA data (in fractions of g, 9.81m/s/s) and earthquake risk categories based on the Modified Mercalli Index *Modified Mercalli Intensity Scale* (n.d.). * Indicates where damage to buildings begins to occur.

years—as such this is a common time interval in which to compute probabilities for exceeding a particular level of ground-motion Z. Wang (2008). Example maps produced by the US Geological Survey report the 2% or 10% probability of exceeding a particular level of shaking in the next 50 years, respectively equivalent to the maximum shaking expected for any earthquakes within a 2,475 and 475-year return period Baker (2008). The reported shaking is, in fact, the median value of a distribution; the standard deviations represent the uncertainty on the estimate, based on unknowns in the seismic source or uncertainties in the GMMs. This statistical distribution of reported shaking forms the basis of our approach.

In the PNW, seismic hazard is controlled almost entirely by the Cascadia Subduction Zone (CSZ) system, where the Juan de Fuca, Gorda, and Explorer tectonic plates sink beneath the North American plate. Here, seismic energy comes from three main types of seismic sources or earthquakes. (1) Events that occur along the subduction zone interface itself (the "megathrust") K. Wang and Tréhu (2016). This subduction system is very large (>1000 km long, extending 40 km beneath the Earth's surface). Earthquake magnitude increases with the area of fault that breaks, which means that earthquakes that rupture even a portion of the subducting interface can produce very large (>**M**8.5 or 9) earthquakes. (2) Deep (∼30 km or more down) earthquakes that occur within the subducting slab ("inslab" earthquakes) Preston, Creager, Crosson, Brocher and Trehu (2003). While these are not as large in size as megathrust events, they are often very energetic for their magnitude and can produce strong and damaging high frequency shaking. Because these happen at great depth within the downgoing plate, they tend to occur beneath the coastline or population centers in the PNW, such as the 2001 Nisqually earthquake beneath Seattle. (3) Shallow (<35 km deep) Wells, Blakely, Wech, McCrory and Michael (2017) earthquakes that occur within the overriding continental crust ("crustal" earthquakes). While these can be the smallest of the three types of events, because they occur much closer to the surface, they potentially cause strong shaking.

Although megathrust earthquakes are the only events that can produce large **M**9 earthquakes with widespread strong shaking, inslab, and crustal earthquakes produce smaller, but more frequent earthquakes that occur closer to population centers. Such inslab and crustal earthquakes thus contribute significantly to seismic hazard, depending on the return period of interest. Overall, as most of these seismic sources are associated with the subduction zone, the greatest seismic hazard and possible ground-motions in the PNW are near the coast, and to the west of the Cascade mountains.

**Internet Infrastructures and Earthquakes.** Analyzing the resilience of infrastructures Agarwal et al. (2011); Bush, Maennel, Roughan and Uhlig (2009); Doyle et al. (2005); Eriksson, Durairajan and Barford (2013c); S. Gorman (2005); S. P. Gorman, Schintler, Kulkarni and Stough (2004); Heegaard and Trivedi (2009); Ho, Tapolcai and Mouftah (2004); Kant and Deccio (n.d.); Katz-Bassett et al. (2008); Willinger and Doyle (2002); Wu, Zhang, Mao and Shin (2007); Zhou (2010), fault detection/localization Glatz and Dimitropoulos (2012); Katz-Bassett et al. (2012); Quan, Heidemann and Pradkin (2012), and development of resilient routing protocols Andersen, Balakrishnan, Kaashoek and Morris (2001); Gummadi, Madhyastha, Gribble, Levy and Wetherall (2004); Hansen, Kvalbein, Cicic and Gjessing (2005); H. Wang et al. (2007); Zhu, Bavier, Feamster, Rangarajan and Rexford (2008) has been the focus of many prior efforts. While studies analyzing the impact of natural disasters (such as hurricanes, wildfires, climate change, and storms) on the Internet are numerous Anderson, Barford and Barford (2020); Cowie, Popescu and Underwood (2005); Durairajan et al. (2018); Eriksson, Durairajan and Barford (2013b); Madory (n.d.); Padmanabhan et al. (2019); Schulman and Spring (2011), there are few that consider extensive levels of infrastructure damage due to earthquake shaking Esposito et al. (2018); Fukuda et al. (2011); Leelardcharoen (2011), and none in PNW. For example, the Kaikōura earthquake in New Zealand produced a maximum recorded PGA of 3.0g near the epicenter, and 1.3g more than 100km away from the fault rupture. Two Internet eXchange Points were impacted: one sustained internal damages to equipment and required new hardware to return functionality in that region, while the other exchange was isolated due to damages to surrounding fiber connections, requiring 1km of replacement cable. Kaikōura's East Coast Link cable sustained 6 breakages and aerial fiber cables sustained stretch-induced damages across riverbanks *Kaikoura quake produced strongest ground shaking in NZ, new research shows* (n.d.). Similarly, the Tohoku earthquake in Japan had a maximum recorded PGA of 2.99 near the epicenter, and 2.7g at 75km away from the fault *2011 Great Tohoku Earthquake, Japan* (n.d.). A study on Japan's SINET4 R&E network showed that even with redundancies such as dual links between core nodes, full recovery of traffic volume took 5-6 weeks near the earthquake's epicenter Fukuda et al. (2011). While these comparisons *qualitatively* demonstrate the damage on infrastructure caused by strong shaking, there are no quantitative studies that detail the direct correlations between the two. This is a necessary avenue for future work, but one that we do not yet tackle here.

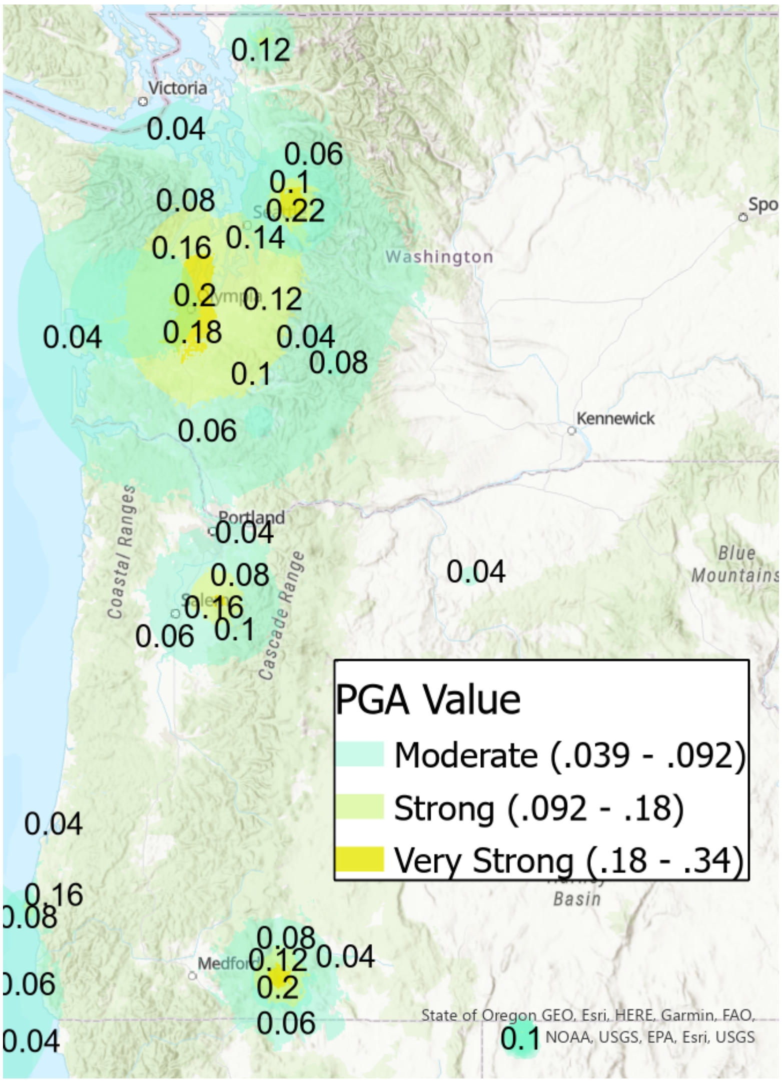


*Figure 1.* PGA Values of historical earthquakes in the PNW.

While seismic hazard in PNW is high, the CSZ is anomalously quiet. Seismicity here is unusually low for an active subduction zone, posing unique challenges to the region in terms of awareness to infrastructure resiliency. Internet infrastructure in the PNW has been installed for just a few decades, within which few significant earthquakes have occurred. This increases the challenge of understanding the full possible impact of a future earthquake. In Figure 10), we show maps of shaking from earthquakes since 1990 with magnitudes greater than 4, for which the ground-motions do not exceed 0.34. The result is that the existing infrastructure has not yet been subject to destructive shaking or suffered severe damages.

There is, however, the unexplored potential that shaking from future earthquakes can have a significant impact on this infrastructure. In particular, these may affect fiber-optic cables, nodes, and cell towers. Terrestrial fiber-optic cables that carry Internet traffic provide protection from a variety of physical damages (e.g., fiber cut). They are packaged in conduits and are buried in trenches along existing right of ways Durairajan et al. (2015). We posit the following risks due to earthquakes in the region. The first is physical damage at the node level (e.g., cell towers), at link level (e.g., physical damage to fiber conduits), and at fiber termination points (i.e., colocation facilities and data centers). A majority of the submarine landing stations are near a seismically active region and terminate at the nearest colocation facility *Evidence for Submarine cables terminating at nearby colocation facilities.* (n.d.). Ground accelerations beyond shaking thresholds published by infrastructure manufacturers will adversely impact fiber deployments: shaking-induced stress may cause state of polarization changes of the light traveling through cables leading to data loss. Furthermore, links may be severed at shaking levels produced by an M9 earthquake.

# CHAPTER III

## DESIGN AND IMPLEMENTATION OF SHAKENET FRAMEWORK

**Overview of ShakeNet Framework.** Motivated by above-mentioned impacts of earthquake-induced shaking on critical Internet infrastructures, we design *ShakeNet*: a framework which brings probabilistic seismic hazard estimates to networking to assess and mitigate the impacts of seismic hazard on Internet infrastructure nodes and links. ShakeNet framework builds on top of a geographic information system (GIS) called ArcGIS and consists of capabilities to (a) categorize infrastructure of varying types (e.g., data centers, cell towers, submarine cables, etc.) into risk groups (e.g., severe, violent, etc.), (b) assess the extent of shaking-induced damages to those types, and (c) identify alternate strategies to mitigate the potential risks. We start by explaining the datasets used in this study, followed by each of these capabilities.

**Internet Infrastructure Datasets.** ShakeNet uses Internet infrastructure datasets from a wide variety of network measurement and community efforts including Internet Atlas project Durairajan, Ghosh, Tang, Barford and Eriksson (2013), OpenCellID *OpenCelliD - The world's largest Open Database of Cell Towers* (n.d.), and others Durairajan et al. (2018, 2015); Kumaran Mani et al. (2020). The dataset is composed of nodes and links of varying types. Node types include data centers, colocation facilities, Internet exchange points (IXPs), submarine landing stations, wireless and microwave cell towers, and points of presence (POPs). Link types include short- and long-haul fiber cables and submarine cables. Our study focuses on Pacific Northwest (PNW) and considers a total of 59 colocation facilities, 422 POPs, 4 IXPs, and 31 data centers. We also examine 213,554 cell towers in the PNW area. Finally, we examine 42,516 miles

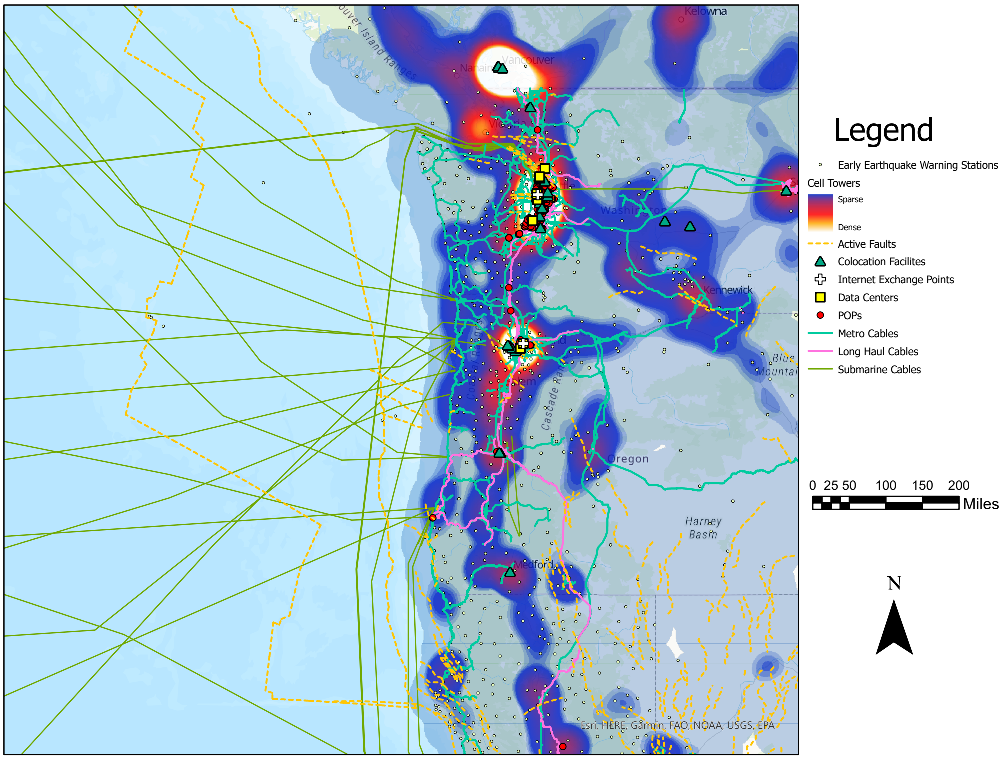


*Figure 2.* Internet infrastructure overlap with mapped faults (yellow dotted lines) in PNW.

of long- and short-haul fiber, and submarine cables terminating in CA, OR, and WA. Fiber cables are represented as polyline features and contain attributes such as provider info. and geodesic length. Nodes are represented as point features and contain attributes such as geographic coordinates and type (e.g., cell towers contain signal type as an attribute LTE, GSM, CDMA, UMTS). While the cable data is accurate in terms of location, there are instances where a cable is split into multiple polyline features; this does not impact the accuracy of our analyses.

Along the US west coast, there is much overlap between areas of high seismic hazard, and critical communications infrastructure. Figure 2 shows the close overlap between fiber-optic cables, colocation facilities, Internet exchange points, long-haul, metro, and submarine cables, cell towers, and mapped active faults.

We hypothesize that earthquakes on these faults could be devastating to Internet infrastructure in PNW; here we apply probabilistic hazard assessment to describe that risk.

**Earthquake Datasets.** ShakeNet uses maps of peak ground acceleration (PGA), derived from probabilistic seismic hazard analyses (PSHA), to quantify the possible effects that future earthquakes may have on infrastructure deployments. We use two sets of probabilistic PGA data which encompass the CSZ: the values of PGA which have a 10% chance of being exceeded in the next 50 years (Figure 3) and the values which have a 2% probability of being surpassed in the next 50 years (Figure 4). These data sets were computed using the USGS national seismic hazard map software for the 2014 map edition Petersen et al. (2015), obtained as raster information, and converted to concentric polygons using *raster contouring* capabilities *ArcGIS Contour (3D Analyst)* (n.d.) in ArcGIS. They use the most up to date fault sources and expected earthquake rates in the western US. We choose 10% and 2% in 50 years as these are typical values considered in structural engineering applications, derived from the average life expectancy of a building (50 years). These probabilities correspond to the average shaking that may occur within a 475 and 2,475 year return period, respectively.

**Categorization of Risk Groups.** To categorize infrastructures of varying types into risk groups, we convert the PGA datasets to Modified Mercalli Index (MMI) as shown in Table 1, and then break them up into risk categories. MMI provides a descriptive scale of earthquake's perceived shaking and potential damage. Categorizing infrastructure into risk groups based on PGA and MMI allows us to estimate the extent of shaking-induced damages by examining the

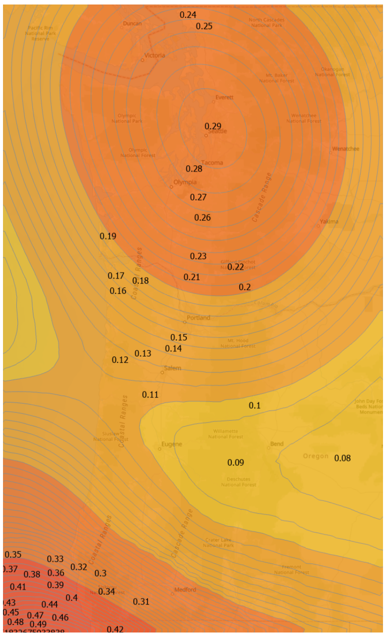

*Figure 3.* Expected PGA with 10% chance in next 50 years.

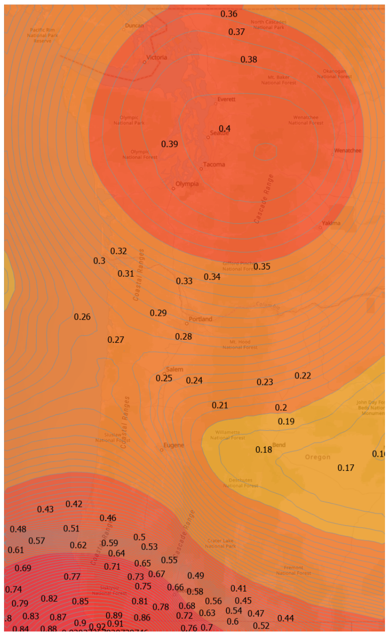

*Figure 4.* Expected PGA with 2% chance in next 50 years.

percentage of infrastructure that may experience shaking, at different probabilities in the next 50 years.

After analyzing data using the overlap method discussed below, we consider how node and link infrastructures could be affected. Similar to buildings, we assume an infrastructure is potentially damaged if the expected PGA exceeds MMI VI (PGA 0.092). By marking these infrastructures, we can reason about the impact that structural damage and a loss of connectivity in that area could have. A novel application of this approach is the ability to view potential fiber routes from the perspective of earthquake shaking risks. Using this perspective, we can design risk-aware deployment and/or routing strategies: maximizing the traffic carried via portions of fiber in the areas with the lowest PGA values. Said differently, we can derive alternate ways to route traffic in the case that the shortest path, albeit with more earthquake risk, has been damaged. Here, we do not consider the fragility or performance of various types of infrastructure; rather, we assume a particular level of PGA will be equally damaging to all.

**Assessment of Shaking-induced Damages to Internet Infrastructure.** We assess the extent of infrastructures damages incurred by earthquake shaking in two steps: (a) analyzing the risks of individual infrastructure types, and (b) combining these individual analyses to determine metropolitan statistical areas (MSAs) Kumaran Mani et al. (2020) with the greatest total risk. We explain these two steps below.

To determine earthquake risk to different infrastructure types, the PGA data is first *contoured*, creating a series of polygons which delineate areas of different minimum and maximum PGA values for the PNW area as shown in Figures 3 and 4. The *intersect* tool *ArcGIS Intersect (Analysis)* (n.d.) in ArcGIS is then used to assign these PGA values to the overlapping infrastructure. The tool takes two feature sets together and generates a new feature set composed of the intersecting geometry from both features. This allows ShakeNet to augment segments of fiber cable or individual nodes and cell towers with minimum and maximum PGA values depending on which PGA polygon the infrastructure in question overlaps with. Infrastructures are then placed into groups by PGA-MMI category and counted via a Python script written in ArcPy to determine the quantity of infrastructure at a given risk category. This script iterates through a given infrastructure dataset (which now contains a PGA value for every cable, node, or cell tower) and returns the quantity of infrastructure within the PGA ranges shown in Table 1. This script was used to create the tables described below. The count of infrastructure within a given group was divided over the total count within the PNW area to calculate percentage values.

To find the overall risk to different MSAs, we use the same overlap method described above, and augment a data set of MSAs in the PNW area with their experienced PGA level. We define polygons based on PGA values for a given probability map (2% or 10%). If an MSA falls on a polygon boundary, we take the average PGA of both polygons to represent the possible shaking at this site. We then use the *Summarize Within* tool *ArcGIS Summarize Within (Analysis)* (n.d.) in ArcGIS to count the quantity of infrastructure per MSA. This allows us to assign MSAs a risk ranking based on their possible exceeded PGA, infrastructure quantity, and population density. Subsequently, a custom script—written using ArcPy *ArcPy* (n.d.)—is used to count and categorize overlap data into risk groups.

**Mitigation of Infrastructure Risks.** Mitigating the infrastructure risks is fraught with challenges. For one, network providers and state governments lack capabilities to (a) holistically combine risks and infrastructures together, (b) quantify risks to infrastructures and categorize them into different scenarios, and (c) identify alternate deployments for the identified scenarios. For example, if connectivity between two MSAs is disrupted by earthquake-induced shaking, how can traffic be dynamically re-routed via other alternate routes that have experienced less damage? Second, while IP routing allows the network infrastructures to dynamically detect and route around failures, shaking-related failure scenarios (like the ones depicted in Table 9) in particular, and natural disasters (e.g., Anderson et al. (2020); Durairajan et al. (2018); Padmanabhan et al. (2019); *Quake shakes up the net, Dec. 2006.* (n.d.); Schulman and Spring (2011)) in general, are shown to have localized effects (e.g., loss of connectivity) for extended periods of time. The main reasons for such localized and temporal Internet outages are typically a lack of geographic diversity in deployments and significant physical infrastructure sharing among providers Durairajan et al. (2015).

To tackle these challenges, we extend the ShakeNet framework with a *route planner*: a scenario-based route planning capability to aid network providers and state governments to maintain the robustness and availability of infrastructures. Route planner is designed to identify alternate fiber deployment routes that are geographically longer but are less susceptible to shaking vs. existing routes that are more prone to earthquake-induced shaking. While network providers already employ backup routes for maintenance and safety purposes, unlike route planner, these backup routes may not explicitly minimize earthquake risk. Given a source and destination, alternate routes with likely lower shaking (PGA) levels are identified by examining the adjacent right of ways to (a) identify existing providers with infrastructure assets (for short-term peering and routing) or (b) deploy new infrastructure deployment locations (for long-term installation). Using route planner, network operators can enhance risk-awareness for deployments by determining routes that minimize predicted shaking and round trip time. The predictive nature of the probabilistic PGA data allows the route planner to be applied in the planning stages of new fiber deployments to harden the resiliency of future infrastructure.

CHAPTER IV

IMPACTS OF EARTHQUAKE SHAKING ON INFRASTRUCTURES IN PNW

**Fiber Infrastructure Risk Groups** Using ShakeNet, we seek an answer to this question by analyzing the fiber infrastructure deployments in the PNW. Table 2 depicts the miles of long-haul and metro fiber infrastructures in PNW categorized based on the PGA-MMI mapping. The overlap of fiber miles is reported for both the expected PGA values for 10% and 2% probability of exceedance values in 50 years. Note that these miles of fiber represent the *minimum miles* that will experience, on average, the specified PGA or MMI. Because the hazard maps are derived from the average expected PGA within that return period, it is possible that lower levels of shaking may be surpassed within that time period (which may increase the miles of fiber affected).

| **PGA (g)** | **MMI** | **Expected PGA - 10%** | **Expected PGA - 2%** |
|---|---|---|---|
| $0.039 < x <= 0.092$ | Moderate | 681 (2%) | 0* |
| $0.092 < x <= 0.18$ | Strong | 14054 (33%) | 681 (2%) |
| $0.18 < x <= 0.34$ | Very Strong | 27782 (65%) | 11246 (26%) |
| $0.34 < x <= 0.65$ | Severe | 0 | 27576 (65%) |
| $0.65 < x <= 1.24$ | Violent | 0 | 3015 (7%) |

Table 2. Miles of fiber categorized based on PGA-MMI mapping, for two different return periods or probabilities of exceedance. *This does not imply that no infrastructure will feel moderate shaking within the 2% in 50 years probability; rather, in this less likely scenario, the shaking at these infrastructure locations will surpass this level of shaking.

From Table 2, we observe that in the next 50 years, 65% of fiber infrastructures in the PNW have a 10% chance of experiencing *very strong* shaking (PGA between 0.18 and 0.34g), and 2% chance of experiencing *severe* shaking (0.34 and 0.65g). Over 3k miles of fiber have a 2% chance of being subjected to *violent* shaking in the next 50 years. This implies that there may be even greater shaking at these sites, though less likely. Further, this analysis suggests that infrastructure providers – with fiber assets in the very strong to violent risk groups – should consider alternate backup paths with fewer earthquake hazards.

Next, we seek to aid network operators in finding where multiple infrastructures are deployed and are prone to high PGA values. We convolve the probability of PGA with number of cables, since the ground motion side already is a probability distribution given by $P\left(PGA > x|50years\right)$. Specifically, we assign—without any lab-based tests—a qualitative "failure likelihood" (e.g., a number between 0 to 1, $p_{failure}$) to cables based on a given PGA they experience. We make a qualitative assumption that MMI VI, which is 10-20%g, will cause moderate damage, as this is also what causes damage on buildings and set $p_{failure} = 0.5$. Cables that experience 1g of ground motion will certainly be damaged/disrupted. Hence, we set $p_{failure}$=1.0. For a given cable, the damage probability would then be: $DP = P\left(damage|50years, Ycable\right) = P\left(PGA > x|50years\right) * P\left(p_{failure}|PGA\right)$. And then for a given region, we will use the damage probability (DP) to obtain the probability of failure/disruption given all the cables by multiplying the number of cables. The count of fiber cables and their failure likelihoods are are shown in Table 3. Similarly, the counts and the damage probabilities are shown in Table 13. The high-risk assets (e.g., 3 cables in the violent category) provide an opportunity to rethink earthquake monitoring using distributed acoustic sensing (DAS) and, more broadly distributed fiber optic sensing (DFOS) for detecting seismic events Lindsey et al. (2017).

To complement Tables 2, 3, and 13, Figures 5 and 6 show the fiber miles for individual providers for PGA values with 2% and 10% probability of exceedance within the next 50 years, respectively. From these figures, we see that Spectrum Business is at the highest risk as it has fiber assets in all higher PGA value

| PGA (g) | MMI | $p_{failure}$ | Count - PGA 10% | Count - PGA 2% |
|---|---|---|---|---|
| 0.039 < x <= 0.092 | Moderate | 0 | 264 | 0* |
| 0.092 < x <= 0.18 | Strong | 0.5 | 7449 | 241 |
| 0.18 < x <= 0.34 | Very Strong | 0.7 | 23061 | 8007 |
| 0.34 < x <= 0.65 | Severe | 0.9 | 0 | 22549 |
| 0.65 < x <= 1.24 | Violent | 1.0 | 0 | 3 |

Table 3. Count of fiber cables categorized based on PGA-MMI mapping (and the corresponding probability of failure for that MMI, $p_{failure}$), for two different return periods or probabilities of exceedance. If a cable passes through multiple risk zones, it is counted for both. We assume that a PGA of 0.092 or below will not cause structural damage to cables. *This does not imply that no infrastructure will feel moderate shaking within the 2% in 50 years probability; rather, in this less likely scenario, the shaking at these infrastructure locations will surpass this level of shaking.

| DP | 1% | 1.4% | 1.8% | 2% | 5% | 7% | 9% | 10% |
|---|---|---|---|---|---|---|---|---|
| Count | 241 | 8007 | 22549 | 3 | 7449 | 23061 | 0 | 0 |

Table 4. Count of fiber cables categorized based on PGA-MMI mapping, and their respective estimated damage probability (DP) in the next 50 years as a percentage, by convolving $p_{failure}$ with the probability of exceeding the level of PGA (2% or 0.02, or 10% or 0.1).

bins, followed by Zayo and Integra. In the analysis of risk, we consider affected miles rather than percentages of a provider's total fiber in the PNW due to the proprietary nature of a provider's data.

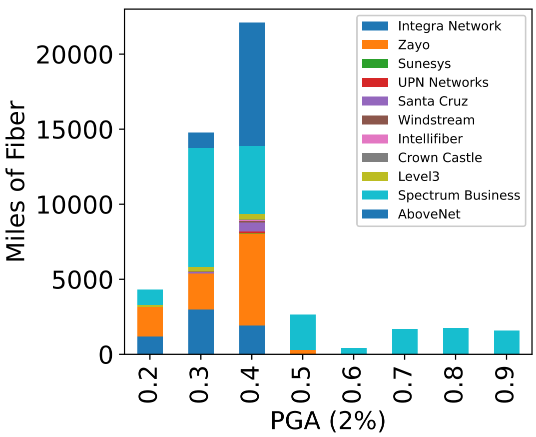


*Figure 5.* Miles of fiber affected for expected PGA with 2% probability.

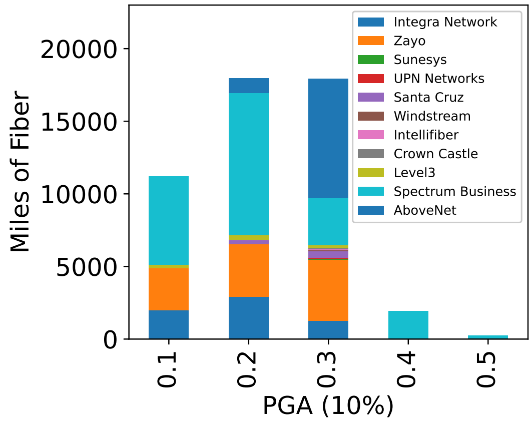


*Figure 6.* Miles of fiber affected for expected PGA with 10% probability.

**Node Infrastructure Risk Groups.** Next, we turn our attention to assess the node infrastructures that are susceptible to strong shaking. Unfortunately, as shown in Figures 7 and 8, the nodes are not distributed uniformly across PNW. For example, the cell tower locations are highly distributed (see Figure 8) whereas the rest of the nodes (as shown in Figure 7) are located close to densely populated metro areas (e.g., Seattle, Portland, etc.). Hence, in our overlap analysis, we separate the cell towers from the rest of the nodes.

Tables 5 and 6 depict the raw count of node types (with percentages) under different risk groups with 10% and 2% probability of exceedance, respectively, in the next 50 years. From Table 5, we note that 39 colocation facilities, 371 POPs, and 29 data centers are prone to *very strong* shaking risk. These infrastructures are also susceptible to *severe* shaking risks if we consider with 2% probability of exceedance. The count (and percentage) of nodes falling into a given risk category in the 10% and 2% PGA is not coincidence. Note that areas with the highest predicted PGAs are also areas with some of the most concentrated infrastructures in the aforementioned metro areas. Meaning that in future earthquakes, these connectivity hubs would be the highest areas of concern.

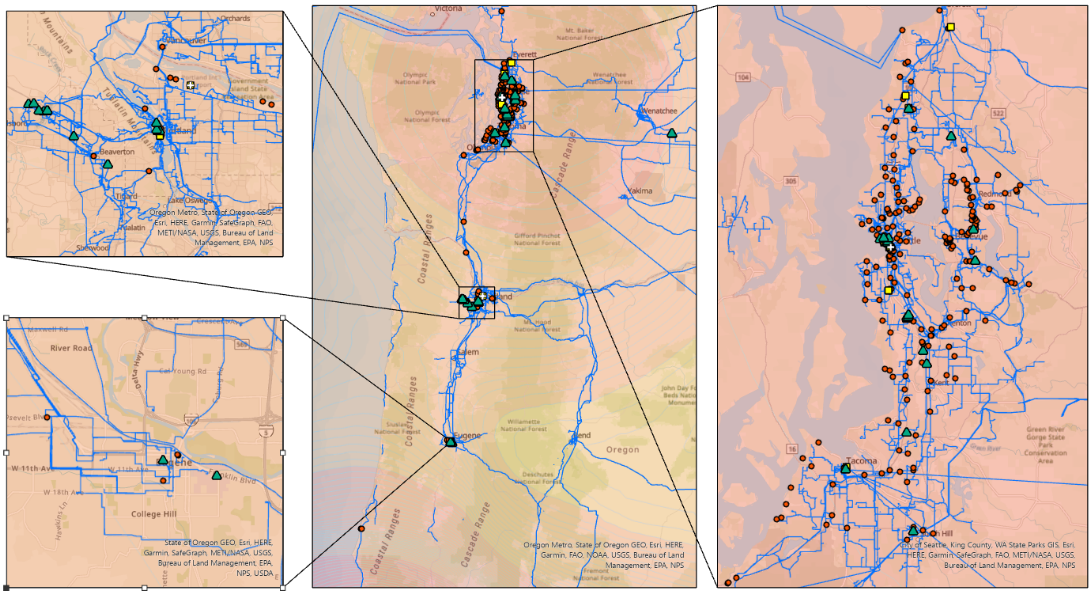


*Figure 7.* Nodes proximal to CSZ. Red circles: POPs, green triangles: colos, yellow squares: data centers, white crosses: IXPs.

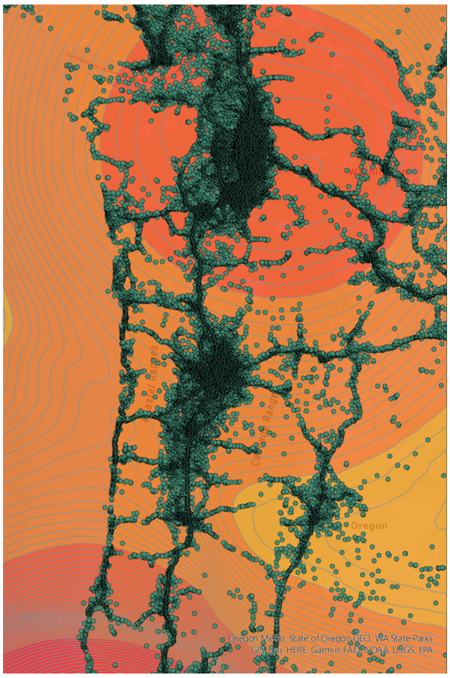


*Figure 8.* Cell towers in PNW.

As mentioned above, the cellular towers—compared to the other node infrastructures—are more broadly deployed across the PNW. Hence their

| PGA | MMI | Colos | POPs | IXPs | Data centers |
|---|---|---|---|---|---|
| 0.092 < x <= 0.18 | Strong | 20 (34.0%) | 51 (12.0%) | 1 (25.0%) | 2 (6.0 %) |
| 0.18 < x <= 0.34 | Very Strong | 39 (66.0%) | 371 (88.0%) | 3 (75.0%) | 29 (94.0 %) |

Table 5. Count of nodes (with percentages) that are prone to earthquake shaking for expected PGAs with 10% probability of exceedance.

| PGA | MMI | Colos | POPs | IXPs | Data centers |
|---|---|---|---|---|---|
| 0.18 < x <= 0.34 | Very Strong | 20 (34.0%) | 51 (12.0%) | 1 (25.0%) | 2 (6.0 %) |
| 0.34 < x <= 0.65 | Severe | 39 (66.0%) | 371 (88.0%) | 3 (75.0%) | 29 (94.0 %) |

Table 6. Count of nodes (with percentages) that have a 2% chance of exceeding a specified level of shaking in the next 50 years.

| PGA | MMI | LTE | CDMA | GSM | UMTS |
|---|---|---|---|---|---|
| 0.039 < x <= 0.092 | Moderate | 2142 (1.75%) | 378 (2.9%) | 241 (1.94%) | 688 (1.04%) |
| 0.092 < x <= 0.18 | Strong | 40213 (32.92%) | 3986 (30.57%) | 3180 (25.54%) | 18810 (28.53%) |
| 0.18 < x <= 0.34 | Very Strong | 79596 (65.17%) | 8636 (66.23%) | 8995 (72.25%) | 46353 (70.31%) |
| 0.34 < x <= 0.65 | Severe | 190 (0.16%) | 39 (0.3%) | 34 (0.27%) | 73 (0.11% ) |

Table 7. Percentage of cell towers (with percentages) that have a 10% chance of exceeding a specified level of shaking in the next 50 years.

| PGA | MMI | LTE | CDMA | GSM | UMTS |
|---|---|---|---|---|---|
| 0.092 < x <= 0.18 | Strong | 1755 (1.44%) | 314 (2.41%) | 175 (1.41%) | 498 (0.76%) |
| 0.18 < x <= 0.34 | Very Strong | 41414 (33.91%) | 4034 (30.94%) | 3343 (26.85%) | 19989 (30.32%) |
| 0.34 < x <= 0.65 | Severe | 75977 (62.2%) | 8340 (63.96%) | 8723 (70.06%) | 44459 (67.44%) |
| 0.65 < x <= 1.24 | Violent | 2995 (2.45%) | 351 (2.69%) | 209 (1.68%) | 978 (1.48%) |

Table 8. Count of cell towers (with percentages) per type that have a 2% probability of exceeding a particular level of shaking in the next 50 years.

deployment locations have a profound impact on how the risk groups look. Tables 7 and 8 show the raw counts and percentages of cell tower infrastructure risk categories for 10% and 2% probability of exceedance in the PNW area; the categories are shown for different technologies (i.e., LTE, CDMA, GSM, etc.). From Table 7, we note that over 97% of cellular infrastructures are in the *strong* to *severe* risk categories. With 2% probability of exceedance, the risk categories shift to *very strong* and *violent* in Table 8.

**What are the impacts of infrastructure outages on the society?** Having looked into the infrastructure risk groups, we next assess the impacts of infrastructure outages on society. To this end, we combine the risk groups with MSAs (from *USA Core Based Statistical Area* (n.d.)) using the overlap analysis capability in ShakeNet. Subsequently, for each return period (10% or 2%), we sort the MSAs by average PGA, then population density, then infrastructure concentration to obtain a combined risk ranking. Note that the values of PGA are uniformly higher in all areas for 2% in 50 years in comparison to 10% in 50 years, thus sorting either by 10% or 2% produces the same ranking.

| **Fiber Cables** | **DCs/IXPs/Colos/POPs** | **Cell Towers** |
|---|---|---|
| Seattle-Tacoma-Bellevue | Seattle-Tacoma-Bellevue | Seattle-Tacoma-Bellevue |
| Portland-Vancouver-Hillsboro | Portland-Vancouver-Hillsboro | Portland-Vancouver-Hillsboro |
| Wenatchee | Eugene | Salem |
| Eugene | Olympia-Tumwater | Eugene |
| Klamath Falls | Bellingham | Olympia-Tumwater |

Table 9. Top 5 MSAs with infrastructures ranked based on high earthquake risks.

Table 9 depicts the top 5 MSAs with the highest infrastructure risks due to shaking. It can be seen from the table that Seattle-Tacoma-Bellevue and Portland-Vancouver-Hillsboro MSAs are of the highest risk in all three infrastructure types. This is primarily due to two factors. First, these MSAs are densely populated and house the majority of fiber and node infrastructures in PNW. Second, since these two MSAs are connected together by fiber infrastructures running along the I-5 interstate and the area between Portland, OR and Seattle, WA has PGA values with predicted shaking ranging from *very strong* to *severe* shaking, the combined infrastructure risks are very high.

**How to minimize the impacts of earthquakes on Internet infrastructures?** To answer this question, we apply ShakeNet's route planner capability for an "average" earthquake scenario that can potentially damage infrastructure deployments in and between Seattle-Tacoma-Bellevue and Portland-Vancouver-Hillsboro MSAs. These two MSAs, together, contain 43 colocation facilities, 399 POPs, and 31 data centers, all connected by 6,681 miles of fiber. This scenario is derived from the above probabilistic analyses, which consider a variety of possible earthquake sources in the region. To establish a baseline, we estimated the speed-of-light RTT based on the shortest path (i.e., via I-5) from the centers of MSAs as ∼3ms. Further, we also noted the minimum, maximum, and average of the PGA in the contours that the fibers pass through for both 10% and 2% probability of exceedance. These statistics are shown in Table 10.

| **Routes** | **Latency** | **Avg 10%** | **Min 10%** | **Max 10%** | **Avg 2%** | **Min 2%** | **Max 2%** |
|---|---|---|---|---|---|---|---|
| Baseline (along I-5) | ∼3ms | 0.24 | 0.17 | 0.29 | 0.36 | 0.29 | 0.4 |
| Yakima - Kennewick | ∼6ms | 0.2 | 0.11 | 0.29 | 0.32 | 0.24 | 0.4 |
| Spokane - Boise | ∼18ms | 0.18 | 0.08 | 0.29 | 0.28 | 0.17 | 0.4 |

Table 10. PGA values and latencies for the shortest vs. other alternate paths from Seattle to Portland.

Using the route planner, we identified two alternate fiber paths with reduced PGAs. First is a path through eastern Washington to Oregon: that is, from Seattle to Spokane, then south to Lewiston, then west to Portland through Kennewick with ∼400 mile (i.e., ∼6ms RTT) increase in fiber span and a PGA reduction of 0.06. The second alternate is through Spokane, WA, and Boise, ID. While this route is much longer (i.e., ∼1200 miles or ∼18 ms RTT) it has the benefit of being even further away from the CSZ and less adverse to risk (PGA reduction of 0.09). These alternate paths could be deployed in the long-term (via new deployments Durairajan and Barford (2017)) as well as short-term (via risk-aware routing Eriksson et al. (2013b)).

**Case study of Integra Long Haul Links.** In addition to identifying risk levels within PNW metro areas, it is equally important to discuss the fiber and cellular connectivity between these metros. We use ShakeNet to reason about the probability of a metro area being disconnected from a fiber provider's network. The risk of disconnection is influenced by two factors: the degree of shaking proximal to a given metro area, and a metro's redundancy, i.e. the number of long-haul links connecting it to the network. Understanding a metro's risk of disconnection provides great insight to the potential impact of the Cascadia earthquake and informs network providers how to best improve resiliency.

One of the largest fiber providers in the PNW is Integra. Spanning a total length of 12187 miles, Integra services all main PNW metro areas within the extent of our PGA data including Eugene, Bend, Salem, Portland, and Seattle. Due to the PNW's reliance on Integra to connect millions of Oregon and Washington residents, it is important to understand the risk of a metro area becoming disconnected from the network. To produce a risk analysis of Integra's long haul links between PNW Metro areas, we use the *intersect* tool to augment Integra's fiber network with our predictive PGA datasets. We then count the number of links connecting each metro to the greater Integra network and calculate the minimum, maximum, and average PGA values for all of these links (seen in Table 11). We use the maximum values as a worst-case scenario and show the maximum PGA of every link in 12. We then use the $p_{failure}$ convolution technique to generate a damage probability table for the links of each metro.

Tables 12 and 11 Show that Portland has the most redundancy at 6 links. Bend and Seattle have the least redundancy with only two links. The Seattle metro area faces the greatest risk of disconnection from the Integra fiber network due to the expected levels of PGA (0.3 at 10% and 0.4 at 2%) and low amount of redundancy. This disconnection would also affect the connectivity of other metro areas south of Seattle. Data would need to be re-routed through Boise, ID to reach Portland and Eugene Oregon. Thus, it is imperative that Seattle's long haul links are structurally re-enforced to minimize connection loss in a disaster scenario.

13 Shows the probability of all links in a route between metros incurring damages. To calculate this metric, we take the $p_{failure}$ of the minimum PGA for a all links between two metros. It is assumed that any areas of PGA higher than the minimum will incur damages. This table presents further evidence that the Portland-Seattle corridor carries the highest risk of disconnection from the Integra network.

| **Metro** | **Link Count** | **MinPGA10** | **MaxPGA10** | **MinPGA2** | **MaxPGA2** |
|---|---|---|---|---|---|
| Eugene | 3 | 0.09 | 0.12 | 0.23 | 0.28 |
| Salem | 5 | 0.09 | 0.15 | 0.23 | 0.28 |
| Bend | 2 | 0.07 | 0.16 | 0.18 | 0.26 |
| Portland | 6 | 0.1 | 0.26 | 0.26 | 0.39 |
| Seattle | 2 | 0.14 | 0.29 | 0.29 | 0.40 |

Table 11. Number of Links per metro, Max and Min PGA values for all links of a metro

**Cost analysis of deploying new fiber using Network Datasets.** As shown in section 4.4, The PNW area's fiber infrastructure would benefit from an increase in redundancy of long haul links between metro areas. Because the Cascadia earthquake event poses such a large threat to PNW fiber infrastructure, Network providers looking to increase redundancy must consider the expected shaking of an area before deploying new fiber. These deployments must minimize shaking, cost, and round trip time to increase network redundancy in an optimized manner. We seek to understand the costs of augmenting the current fiber network

Table 12. Max PGA Value of each link per metro

PGA 10

| **Bend** | **Seattle** | **Eugene** | **Salem** | **PDX** |
|---|---|---|---|---|
| 0.09 | 0.29 | 0.12 | 0.12 | 0.15 |
| 0.16 | 0.29 | 0.12 | 0.12 | 0.15 |
| | | 0.12 | 0.12 | 0.16 |
| | | | 0.15 | 0.17 |
| | | | 0.15 | 0.18 |
| | | | | 0.26 |

PGA 2

| **Bend** | **Seattle** | **Eugene** | **Salem** | **PDX** |
|---|---|---|---|---|
| 0.18 | 0.4 | 0.25 | 0.25 | 0.28 |
| 0.26 | 0.4 | 0.25 | 0.25 | 0.29 |
| | | 0.25 | 0.25 | 0.3 |
| | | | 0.28 | 0.32 |
| | | | 0.28 | 0.32 |
| | | | | 0.39 |

| | Min PGA 10% | $p_{failure}$ | DP | Min PGA 2% | $p_{failure}$ | DP |
|---|---|---|---|---|---|---|
| Eugene-Salem | 0.12 | 0.5 | 5% | 0.25 | 0.7 | 1.4% |
| Salem-Portland | 0.15 | 0.5 | 5% | 0.28 | 0.7 | 1.4% |
| Portland-Seattle | 0.29 | 0.7 | 7% | 0.4 | 0.9 | 1.8% |
| Bend-Portland | 0.16 | 0.5 | 5% | 0.26 | 0.7 | 1.4% |

Table 13. Probability that all links on a route between two metros will incur shaking-induced damages in the next 50 years. Calculated by convolving $p_{failure}$ for the minimum PGA across all links of a route with the probability of exceeding the level of PGA (2% or 0.02, or 10% or 0.1).

with additional routes that will be less prone to shaking induced damages. We use the route planner to estimate these costs.

We use a line geometry dataset of Washington and Oregon state roads provided by OpenStreetMap (OSM) as the basis for choosing additional links. Fiber cables are often deployed along roads due to ease of access, a majority of fiber cables in the PNW are currently deployed along roadways. Treating sate roads as potential fiber cable placement is a reasonable step in planning the placement of additional links between metro areas. We augment the OSM dataset with our predictive PGA data using the *intersect* tool, the same procedure used to reason about PGA levels of long haul links. We use the OSM and PGA data to build an ArcGIS *Network Dataset*, a weighted graph where the roads are the edges, the intersections and junctions are nodes, and the weights are distance and the PGA value proximal to the road segments. ArcGIS is capable of performing many routing operations on Network Datasets including finding the shortest path between a number of stops while avoiding barriers. Cost functions of traversing a path can be specified, we use a cost function that minimizes for both distance and cumulative PGA.

To find the best possible alternative routes to the current fiber network, we place stops at all main PNW metro areas and run an analysis which finds the best path to all stops in any order. The result is a route on state roads that minimizes for distance and shaking risk between Medford, Bend, Eugene, Portland, Seattle, and Spokane. These are the safest and most direct roads on which to build new fiber deployments. In this optimal route, there are many areas which overlap with current fiber deployments, e.g. both current fiber and the optimal OSM route traverse along Interstate I5 in many sections. We isolate the areas of the generated route which do not overlap with current fiber deployments to obtain three potential candidates for risk-aware long haul deployments: Medford-Diamond Lake, Bend-Shedd, and Portland-Seattle. A link between Medford and Diamond Lake Oregon would connect Medford directly to Eugene and Bend, and provide a through line to All other north-lying metro areas. A link between Bend and Shedd would provide increased redundancy to Bend, allowing connectivity directly between Bend, Eugene, and Salem. The only current alternative to connect bend with Eugene/Salem involves traversing through Portland which is a longer route with higher PGA values. An additional link between Portland and Seattle would provide a backup if the current route along the I-5 interstate is compromised.

While avoiding areas susceptible to strong shaking incurs a distance and latency penalty, as well as a cost overhead for deployment (estimated $25,000 per mile of fiber), a marginally slower connection during a disaster recovery scenario is preferable to a lack of connection between metro areas. Seattle and Portland in particular are commercial hubs with high population density and play important roles in connecting the west coast to other parts of the world via undersea cables. Creating alternate links between these metros is instrumental to preserving connectivity in the PNW and hardening fiber infrastructure in preparation for the CSZ earthquake.

| **Routes** | **Length** | **Est. Cost** | **RTT** | **Avg 10%** | **Min 10%** | **Max 10%** |
|---|---|---|---|---|---|---|
| Medford - Diamond Lake | 161 | 4,025,000 | ~1.72ms | 0.175 | 0.11 | 0.23 |
| Bend - Shedd | 180 | 4,500,000 | ~1.93ms | 0.095 | 0.09 | 0.1 |
| Portland - Seattle | 242 | 6,050,000 | ~2.59ms | 0.2 | 0.19 | 0.27 |
| Baseline Bend-Shedd via PDX | 317 | N/A | ~3.41ms | 0.122 | 0.08 | 0.16 |
| PDX - Seattle Tertiary Option | 325 | 8,125,000 | ~ 3.48ms | 0.21 | 0.15 | 0.28 |

Table 14. Backup PGA 10 - Bend to Shedd via PDX is baseline already existing route

| **Routes** | **Length** | **Est. Cost** | **RTT** | **Avg 2%** | **Min 2%** | **Max 2%** |
|---|---|---|---|---|---|---|
| Medford - Diamond Lake | 161 | 4,025,000 | ~1.72ms | 0.475 | 0.24 | 0.68 |
| Bend - Shedd | 180 | 4,500,000 | ~1.93ms | 0.21 | 0.18 | 0.24 |
| Portland - Seattle | 242 | 6,050,000 | ~2.59ms | 0.355 | 0.31 | 0.4 |
| Baseline Bend-Shedd via PDX | 317 | N/A | ~3.41ms | 0.24 | 0.17 | 0.30 |
| PDX - Seattle Tertiary Option | 325 | 8,125,000 | ~ 3.48ms | 0.36 | 0.27 | 0.4 |

Table 15. Backup PGA 2 - Bend to Shedd via PDX is baseline already existing route

We place additional barriers along these newly defined routes and run another iteration of the routing process to reason about a scenario where both the primary

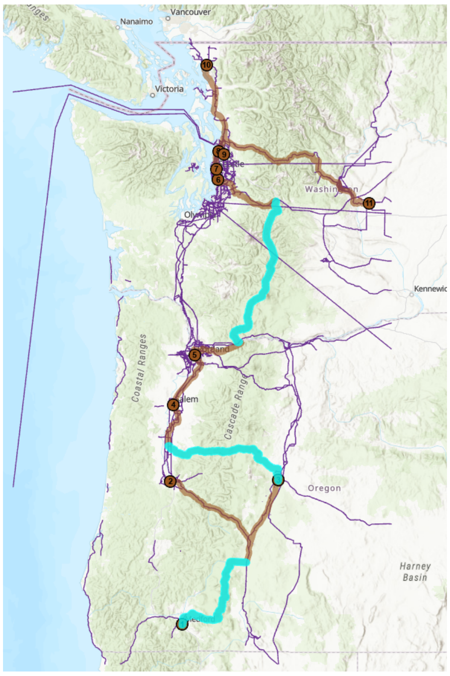


*Figure 9.* Current Fiber Deployment (Purple) with Plan B route (Brown), additional links highlighted in blue


*Figure 10.* OSM Road Dataset (Blue) with Plan B route (Brown)

and backup options are damaged. These tertiary routes that arise for traffic between Portland and Seattle showcase a trade off between length/cost and safety.

**Re-enforcing Cell Tower Connectivity Between Metro Areas.** In addition to constructing alternate routes for fiber links, our route planning tools can also be used to construct routes for wireless infrastructure. Should wired links be compromised, cell tower communications would become an essential channel of communications for first responders in a disaster scenario. As such, there is great incentive to maintaining the highest amount of connectivity possible during a disaster scenario. Cell towers are not impervious to shaking-induced damages, in recent years there have been legislative pushes in Los Angales California to implement re-enforced cell towers capable of withstanding earthquake induced shaking. However, the scale of the PNW is much larger. With over 120,000 cell towers between Washington and Oregon, it is not a feasible solution to re-enforce all towers. We use the route planning capabilities of ShakeNet to identify cell tower corridors which if re-enforced, would create a resilient cell tower backbone across the PNW, allowing cellular communications between metro areas with minimal tower re-enforcement.

Before performing a shortest path analysis, we build a dataset of connectivity lines from the set of cell tower points. Assuming a worst-case connection range of 15 miles, use ArcPy to create connectivity line features between all cell towers within range. We then build a network dataset from the connectivity lines and run a shortest path analysis with stops between all PNW metro areas. Much like the fiber routes, the most optimal cell tower route between metros lies along the I5 interstate highway. This area has proven to be an overall risk bottleneck for the PNW as many metros rely on infrastructure along the I5 to maintain connectivity with the greater region. We derive a backup cell tower routing option should this bottleneck segment of infrastructure fail. As depicted in 11, the most optimal backup route involves a detour west along the coast between the Portland and Seattle metro areas. Re-enforcing Cell towers along the I5, and a backup path such as the detour depicted in 11 would drastically increase chances of maintaining connectivity between metro areas during a disaster scenario, allowing for essential communication of first responders and other emergency response personnel.

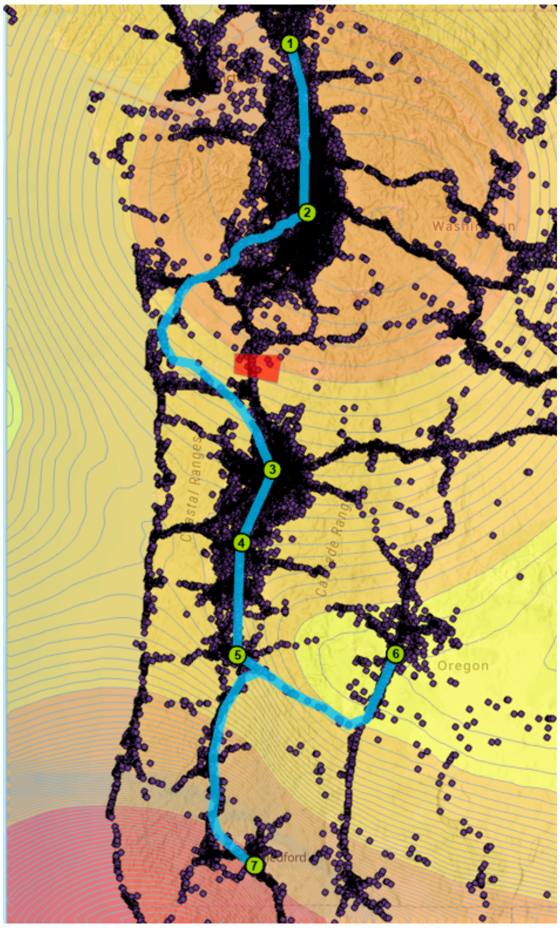


*Figure 11.* Most Optimal cell tower route connecting Metro areas in PNW given a barrier along I5 (Green: route stops, red: barrier, blue: route)

## CHAPTER V

## SUMMARY AND FUTURE WORK

**Summary.** To understand and mitigate (future) earthquake-related risks on Internet infrastructure in the PNW, we have devised a GIS-based framework called ShakeNet. ShakeNet uses a probabilistic approach to categorize the infrastructures into risk groups based on PGA and MMI, and estimate the potential extent of shaking-induced damages to infrastructures. Our analysis shows that ∼65% of the fiber links and cell towers are susceptible to violent earthquake shaking. Further, infrastructures in Seattle-Tacoma-Bellevue and Portland-Vancouver-Hillsboro MSAs have a 10% chance to incur very strong to severe earthquake shaking. We design a route planner capability in ShakeNet and show that it is possible to mitigate the impacts of shaking risks by identifying longer albeit less-risky paths.

**Future Work.** Further development of ShakeNet will use USGS ShakeAlert earthquake early warning messages to re-route traffic during the occurrence and growth of an earthquake to maintain critical Internet functionality for post-disaster responses. We also plan to extend ShakeNet and explore multi-hazard events (i.e., a cascading sequence of natural disasters such as aftershocks followed by a tsunami) which are expected to severely impact the Internet infrastructures. Similarly, earthquake-related permanent ground deformation (ground failure such as landslides and liquefaction) pose a significant threat to Internet infrastructures. For the former, we plan to consider Short-term Inundation Forecasting for Tsunamis (SIFT) *NOAA Tsunami Forecasting System (SIFT)* (n.d.) from NOAA tsunami forecasting *NOAA Tsunami Forecasting* (n.d.) and do a multi-layer analysis of risks from shaking and tsunamis. For the latter, we will use probabilistic estimates of ground failure from models such as Allstadt et al. (2016); Nowicki, Wald, Hamburger, Hearne and Thompson (2014); Nowicki et al. (2014); Zhu et al. (2008). We will expand ShakeNet's route planner by considering individual provider networks: with this analysis, new routes can be produced with minimized risks for each provider.

Finally, ShakeNet can be extended to a performance-based earthquake engineering (PBEE) paradigm Naeim, Bhatia and Lobo (2001), which provides measurable assessments of the potential seismic performance of a system given decision-makers' determinations of its necessary functional level. This requires understanding the performance of various infrastructure components when exposed to a certain level of shaking. The resulting performance is convolved with 2% and 10% PGA estimates like we have shown here, to determine risk, and, finally, obtain a performance-based aspect of the infrastructure by defining various tolerance levels (e.g., partial functionality, increased latency but full functionality, etc.). This PBEE methodology can also be expanded with infrastructure vibration tolerances to reason about unique failure likelihoods for cables, cell towers, and buildings (data centers). This expansion is non-trivial and requires extensive research into tolerance thresholds for many types of infrastructures, potentially using numerical or physical modeling. Currently, no known solution exists.

**Open Problems.** As indicated by the section above detailing Future Work, there are many directions ShakeNet can expand in to reason about open problems. Such problems include:

1. Combining ShakeNet with early warning systems to dynamically re-route data

2. Applying PBEE notions of full, partial, and essential functionality to various infrastructure types

3. Utilizing vibration-tolerance specification of node buildings, cell towers, and fiber conduits to produce more accurate damage probabilities.

4. Assessing how shaking affects the Bit Error Rate of data in a fiber cable to predict packet loss between Metro areas in a CSZ earthquake scenario.

**Lessons Learned.** Producing ShakeNet was my first endeavor in the fields of Internet Measurements and Seismology. Over the course of production I came into first-contact with many new concepts, ideas, and methodologies. Some of my most important takeaways are as follows:

1. This work required a large amount of background research into Seismology and Geology: Understanding the metrics of earthquakes (PGA, MMI, etc) and geological makeup of the Cascadia Subduction Zone were essential to assessing the potential impact of an earthquake on the PNW's Internet infrastructure.

2. Before working on ShakeNet, I had no formal knowledge of Internet Measurements or technical background of Internet infrastructure. Working on this project taught me about the complex and dynamic systems which make up the Internet on local and global scales. Furthermore, I now understand the Internet's fragility as well as the many systems in place to provide safety and ensure operability in catastrophic conditions.

3. ShakeNet was my frist experience with large-scale geospatial data analysis. Through Working with geometric data in ArcGIS, I learned to craft efficient

analysis pipelines and produce tool sets in Python which integrate with ArcGIS's proprietary objects and methods.

4. In my analysis, I applied probabilistic concepts learned from Statistics and Discrete Mathematics courses to reason about Internet infrastructure's susceptibility to damages.

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